Proterozoic Crustal Evolution in Southwestern Africa

by Chris Hartnady, Pieter Joubert and Clive Stowe

This article reviews recent work on the Precambrian shield of Southern Africa between the northeastern, 3.5 Ga-old, Kaapvaal and Zimbabwean Archaean nuclei and the south-western Late Proterozoic-Early Palaeozoic belts. In the latter part of the subcontinent, no confirmed trace of Archaean crust has yet been found, the oldest fragment being the 2.0 Ga-old, volcanoplutonic Richtersveld Subprovince. Paleomagnetic reconstructions suggest the existence in the late Precambrian of the Adamastor Ocean, separating cratonic blocks in southern Africa and extending into South America and Antarctica.

Proterozoic Tectonic Divisions

Southern African Proterozoic provinces are generally considered to have originated during three main chelogenic cycles, known elsewhere in Africa as the Eburnean, Kibaran and Pan-African episodes. A clearer pattern (Fig. 1 and Table 1) of tectonic subprovinces and terranes is now emerg-

ing (Stowe, Hartnady and Joubert, 1984), complicating the earlier view of extended Precambrian crust-forming cycles and showing that individual parts of the major provinces evolved separately over time-scales much briefer than 500 to 1,000 Ma. For the present, however, a three-fold division into Early, Middle and Late Proterozoic crustal provinces is retained.

In the Early Proterozoic Kgalagadi (Kalahari) Province, the Kheis and Magondi subprovinces evolved between 2.0 and 1.7 Ga in equivalent positions along the western flanks of the Kaapvaal and Zimbabwe (Rhodesian) Archaean provinces. Largely concealed by an extensive Phanerozoic sedimentary veneer, their internal subdivision is inferred from geophysical surveys, isolated exposures and borehole data. The Middle Proterozoic Namaqua Province is a broad high grade region extending for 2,000 km across the southern flank of the Kaapvaal Province.

The Natal, Gordonia and Bushmanland subprovinces consist of supracrustal paragneisses, orthogneisses, charnockites, granitic plutons and pegmatite belts, with a 1.2-0.9 Ga metamorphic-plutonic history. The Richtersveld Subprovince, a low-grade Early Proterozoic (2.0-1.8 Ga) volcano-plutonic complex, is widely separated from the Kgalagadi Province by younger high-grade terranes. The enigmatic Rehoboth Subprovince is hidden beneath relatively undeformed Late-Precambrian, Nama and Permian to Jurassic, Karoo cover sequences above an unknown basement.

The Late Proterozoic to Early Palaeozoic Damara Province includes the Khomas and Swakop belts of Namibia (the Damara Orogen *sensu stricto*), the Saldania Belt (SW Cape Province) and the Gariep Belt (Atlantic coastal region). Recent tectonic and geochronological studies in these subprovinces suggest that "Pan-African" orogeny occurred during at least two distinct phases, the most recent culminating at about 530 Ma ago (Miller, 1983a).

Regional gravity and aeromagnetic surveys in the central, sand-covered Kalahari region define crustal tectonic units. For example, continuity between the Damara Province and the Lufilian Arc and Zambezi Belt of central Africa is indicated by prominent linear magnetic anomalies

Figure 1: Major tectonic provinces and subprovinces of Southern Africa. K = Kalahari Line; P = Pofadder Shear Zone; S.C.C.B. = Southern Cape Conductive Belt; T = Tshane and X = Xade Mafic Complexes.

TABLE 1.

SUMMARY OF TECTONIC PROVINCES IN SOUTHWESTERN AFRICA

PROVINCE and Subprovince	Terrane	Regional Geological Features	Regional Trend	Deformation Ages (Ma)
<u>DAMARA</u>				
Kaoko Belt	---- ----	Northern "arm" of the Damara Orogen.	North	----
Swakop Belt	---- ----	Low P, high T belt with main igneous and plutonic activity.	ENE	675-530
Khomas Belt	Kuiseb	High P, low T belt. Intense asymmetric thrust and shear belt.	ENE	675-530
	Hakos-Auas	Naukluft nappe complex, SSE-vergent.	ENE	675-530
Zambezi Belt	---- ----	Medium-high grade paragneiss and granite plutons.	ENE	1200-530
Gariep Belt	Marmora	W-vergent allochthonous thrust complex with "ophiolitic" Grootderm sheet.	N-S	700-530
	Port Nolloth	Thrust complex.	NNW	686-525
Saldania	Boland	Clastic and carbonate sequence with thrusts.	NW	520
	Swartland	Phyllitic terrane, polyphase deformation and NNW sinistral shears.		
	Tygerberg	Greywacke/phyllitic turbidites, sub-vertical folds and NNW shears.		
<u>NAMAQUA</u>				
Natal	northern	Tugela gneissic complex thrust over low-grade "ophiolite" sequence.	E-W	1200-900
	southern	Granulitic gneiss, charnockite and granite. Polyphase deformation.		
Bushmanland	various	Para and orthogneiss; charnockite and granite. Several phases of deformation including early S-vergent recumbent folds and thrusts and late NW, dextral shear zones.	var.	----
			E-W	1700-1000
Gordonia	Kakamas	High-grade supracrustals, granulite, orthogneiss, charnockite, late granites. Polyphase folding including early SW-vergent thrusts and late NW, dextral shears.	NW	1200-1000
	Upington	Transitional terrane of Kheis Province rocks, re-folded and metamorphosed by Namaqua orogeny. Includes also Namaqua-age volcanics (Jannelsepan and Wilgenhoutsdrif). NE-vergent isoclines and thrusts. Late dextral faults.	NW	1300-950
Rehoboth	---- ----	Late-Proterozoic to Mesozoic platform cover above unknown basement.	----	?
Richtersveld	---- ----	Calc-alkaline basalt, andesite, acid lavas and volcanoclastics deformed by "Orange River" orogeny, intruded by Vioolsdrif Suite.	E-W	2000-1730
<u>KGALAGADI</u>				
Kheis	various	Thin-skin fold and thrust belt, E-vergent. Quartzite, phyllite metabasite sequence.	N-S	2100-1760
Magondi	various	Fold and thrust belt, SE-vergent, orthoquartzite-carbonate sequence.	NNE	2000
<u>KAAPVAAL</u>	---- ----	Archaean craton, greenstone belts, tonalitic gneiss, granite.	ENE	3600-2600
<u>ZIMBABWE</u>	---- ----	Archaean craton, greenstone belts, tonalitic gneiss, granite.	var.	3600-2600

across northwestern Botswana. An interpreted contour map of depth to magnetic basement shows the southern Damara-Zambezi belt margin as a thrust front, flanked along its southeastern side by deep marginal basins (Pretorius, 1984).

Continuity between the Natal and Bushmanland belts of the Namaqua Province, and the position of the Archaean craton-Namaqua Province boundary beneath the Mesozoic cover and Cape Fold Belt, is indicated by a characteristic gravity profile signature (De Beer and Meyer, 1983). The "Kalahari Line" along the 22°E meridian, separating deep (> 15 km) magnetic basement in the west from the Kheis Belt and shallow cratonic basement to the east (Hutchins and Reeves, 1980), is a distinct positive gravity and magnetic anomaly marked also by the Tshane and Xade mafic-ultramafic complexes. It might be a pre-Namaqua rifted continental margin.

The buried southern boundary of the Namaqua Province has been located by geomagnetic induction surveys in a 1,200 km-long feature now called the Southern Cape Conductive Belt, coincident with the major Beattie static magnetic anomaly (De Beer et al., 1982). Combined geophysical data indicate the presence of a highly conductive, magnetic and dense rock mass at relatively shallow crustal depth, possibly partially serpentinized basic rocks marking oceanic crust subducted from the south. This suggests that the Namaqua Province did not form intracratonically but rather along a continental margin as a Cordilleran or Andean-type mountain belt (De Beer and Meyer, 1983).

The Early Proterozoic Kheis Belt

The Kheis Belt, extending north along the western margin of the Kaapvaal Province for some 400 km into southern Botswana, is structurally quite distinct from and older than the Namaqua Province. Recent field mapping has shown that

Figure 2: Profiles of thin-skinned thrusting across the Kheis Belt. Faults: Bk - Brakbos; Br - Brulpan; D - Doornberg; J - Jebeko; Sb - Straussburg; Sy - Strydenberg.

it is a thin-skinned fold-and-thrust belt (Fig. 2) developed in a 2.0 Ga-old quartzite-phyllite and amphibolite sequence (Stowe, in press). A transition from the epeiric carbonate and iron-formation shelf deposits of the Transvaal basin (2.5-2.3 Ga) to the Kheis Belt is marked by unconformable fluvial red-bed type quartzites deposited as a series of prograding clastic wedges from the cratonic source terrane. The basal Hartley Formation basalts provide an older age limit of 2068 ± 70 Ma (Rb-Sr) for this sequence (Barton and Burger, 1983).

Extensive thrusting both within and beneath the succeeding quartzite and phyllite sequence has produced a tectono-stratigraphic succession consisting of at least five major thrust sheets (shown by Roman numerals in Fig. 3) separated by mylonites. Mafic schist and amphibolite are particularly abundant along the western margin of the Kheis Belt, suggesting a volcanic fringe. Thrusting was directed eastwards and large-scale recumbent folds (Fig. 4) display eastwards tectonic vergence, towards the craton. Metamorphic grades are low, but rare kyanite that has escaped widespread retrograde sericitization suggests earlier high pressures.

Lenses of gneissic granite incorporated in some of the thrust slices are not interpreted as basement wedges because in detail they display intrusive contact relationships. Minimum U-Pb model ages range from 1485-1268 Ma (Barton and Burger, 1983) near the Namaqua boundary in the south to about 1800 Ma in the north.

The Middle Proterozoic Namaqua Province

The Namaqua Province was recently the focus of a National Geodynamics Program involving five South African universities and research institutes and summarized in Blignault et al. (1983), Joubert (1981) and Stowe (1983, 1984). It is a regional gravity high, suggesting high-density lower crust different from that of the Archaean crustal provinces. Deep seismic refraction profiles across Namaqualand indicate a relatively high velocity crustal layer (~ 6.6

Figure 3: Regional pattern of tectonic terranes in the Gordonia and Kheis Belts. Roman numerals indicate thrust sheets.

Figure 4: A large-scale recumbent fold and thrust in the Skeurberg, Kheis Belt. Landrover for scale.

km/s), perhaps approaching dioritic-gabbroic composition, at 15-40 km depths beneath the granulite terranes (R.W. Green, personal communication, 1985).

Recent Nd isotope studies of lower crustal xenoliths from Mesozoic kimberlites cutting the Namaqua Province suggest that, in contrast to the Archaean craton sub-crustal lithosphere, a major part of the lithosphere beneath the Proterozoic belts stabilized around 1.4-1.0 Ga (Hawkesworth, personal communication, 1984). New Rb-Sr, Pb-Pb, Th-Pb and Sm-Nd isotopic data (Barton and Burger, 1983) allow the recognition of at least two significant crust-forming events in Namaqualand. An older "Orange River" orogeny is indicated by 2.0-1.7 Ga ages in the Richtersveld and adjacent sectors of the Bushmanland Subprovince, and a younger "Namaqua Event" is dated at about 1.3-1.0 Ga.

In the Richtersveld Subprovince (Fig. 5) mafic and felsic lavas, ignimbrites and volcanic rocks are interbedded with minor sediments (Blignault et al., 1983), including distinctive quartzites, pelitic schists and banded iron formations. In high-grade metamorphic areas, the supracrustals are transformed to amphibolitic and quartzofeldspathic gneisses containing some calc-silicate rocks, aluminous metapelites with sillimanite nodules, and also cordierite-anthophyllite rocks.

The Vioolsdrif Suite penecontemporaneously intruded this calc-alkaline volcanogenic pile and covers some 30,000 km². Petrographically and geochemically, it consists almost entirely of I-type granitoids and com-

pires with similar igneous rocks of Cenozoic age found along island-arc and active continental margins (Reid and Barton, 1983). An early phase of basic to intermediate magmatism at about 1.9 Ga was followed by felsic plutonism at 1730 ± 20 Ma (Reid, 1982). The currently preferred model involves the 2.0-1.9 Ga formation of an island-arc complex and its later remobilization at depth along an active continental margin (D.L. Reid, personal communication, 1984).

Near the southern boundary of the Richtersveld, irregularly shaped amphibolite-serpentinite bodies of gabbro through olivine norite to peridotite are dated at 1971 ± 96 Ma (Reid, 1982). Farther south a relatively narrow zone of grey biotite gneiss with mafic intrusives separates the Richtersveld and Bushmanland Subprovinces. Mafic rocks on this sinuously folded, 350 km-long "Wortel Belt" (Fig. 5) may also have a 2.0 Ga age (H.S. Welke and C.B. Smith, personal communication, 1984). It extends westward into the Groothoek Thrust (Blignault et al., 1983), a major north-dipping mylonitic ductile shear zone. Along this southwestern boundary, the low grade Richtersveld Subprovince was thrust southwards over the higher-grade northern terrane of the Bushmanland Subprovince.

The Bushmanland Subprovince (Fig. 5) consists of intensely deformed, high grade gneisses, granulites and granitoids. A distinction between pre-Namaquan "basement" rocks and Namaquan supracrustal cover rocks is difficult and controversial. Opinions divide over the classification of certain paragneisses, whether they are of sedimentary or volcanic origin, and how they might be distinguished from syntectonic orthogneisses. Added to this is the question of whether much of the Bushmanland Subprovince is tectonically and anatexically "reworked" Archaean crust, as Kröner (1977) argued, or reworked Early Proterozoic crust of mixed volcano-plutonic character, similar to that exposed in the Richtersveld Subprovince. Certain heterogeneous banded and "grey" gneiss assemblages might be vestigial basement in which a deformation phase predating the surrounding aluminous schistose gneisses and quartzites can be recognized.

Figure 5: The pattern of tectonic terranes in the Richtersveld and Bushmanland Subprovinces.

AT - Aua's Terrane;
GT - Garies Terrane;
JPB - Jannelsepan Belt;
KT - Kakamas Terrane;
OT - Okiep Terrane;
PT - Pela Terrane;
TVB - Tantalite Valley Belt;
UT - Upington Terrane;
VT - Vioolsdrif Terrane;
WB - Wortel Belt;
GD - Groothoek Thrust;
WD - Wilgenhoutsdrif Formation.

GSC

In the Bushmanland Subprovince, the Aggeneys Sequence hosts the giant stratiform base metal deposits of Aggeneys and Gamsberg (Fig. 6). A new depositional model (J.M. Moore, personal communication) for these metasedimentary paragneisses involves a three-fold division into (i) a northern continental/shallow marine quartzitic-aluminous facies, (ii) a central deeper marine facies of more biotitic gneisses and carbonate rocks, and (iii) a southern shallow marine facies of impure feldspathic quartzites and poorly sorted pelitic rocks. There is still some doubt about whether these facies were actually coeval in a single sedimentary basin, or represent different assemblages belonging to tectonically-juxtaposed, formerly separated terranes. Metavolcanic amphibolites in the upper part of the sequence have a Sm-Nd isochron age of 1597 ± 112 Ma (P.J. Betton, personal communication, 1984). If problematic ~ 1300 Ma Pb model ages (Koeppel, 1978) for the supposedly syngenetic, stratiform base metal ore deposits are ignored, then the Bushmanland metasedimentary gneisses probably accumulated between 1.7 and 1.6 Ga.

The dominant, mainly E-W fabric in the Bushmanland Subprovince has been related to a regional metamorphism dated at ~ 1.2 Ga (Clifford et al., 1981). The main isoclinal folds are south-vergent and the large open, E-W trending, folds that extend across Bushmanland are a later phase. Subsequently, major and many minor shear zones developed, mainly dextral, on NW and ENE directions, followed along the west coast by the northerly trending, sinistral Pan-African shear zones and faults.

Figure 6: Aerial view of a large open fold structure in Bushmanland with Aggeneys Mountain in the background.

Extensive megacrystic and augen gneisses, dated at ~ 1.2 Ga and younger, intrude paragneissic rocks as subhorizontal concordant sheets of batholithic proportions. Their granitoid precursors were probably produced by crustal anatexis, reworking a 2.0–1.9 Ga crustal protolith similar to the Vioolsdrif Suite and its associated metavolcanics (Reid and Barton, 1983). Late-tectonic granites followed and although geochemically variable, they are similar in appearance, field relationships and ~ 1.2 – 1.1 Ga isotopic ages. Emplacement of the late-tectonic plutons was subject to the NNW-oriented Gordonia tectonic control, superimposed obliquely across the regional E-W Namaqua trend. Important copper-bearing mafic rocks and anorthosites, occur only within the region of granulite facies metamorphism, dated at 1.1 Ga.

Metamorphic zonation and thermal history in the western Namaqua Province reveals no detectable pressure variation but very steep palaeogeothermal gradients. D.J. Waters (personal communication, 1984) proposes that magmatic heat transfer in the crust explains the massive regional thermal anomalies in the highest grade metamorphic region of southern Bushmanland.

The northwest trending Gordonia Subprovince was at first a zone of convergent thrusting and folding, followed by an estimated minimum of 140 km of dextral shearing (Stowe, 1984). It incorporates a line of volcano-plutonic amphibolite complexes (Jannelsepan Formation) with calc-alkaline chemistry (Geringer, 1979), separating the Upington Terrane from the high-grade Kakamas Terrane (Fig. 3). Metamorphism at around 1.2 Ga was followed by retrograde shearing at about 1.1 Ga. Its western margin is marked by the Tantalite Valley Belt (TVB on Fig. 5) of metagabbro, gabbro, troctolite, pyroxenite and peridotite intrusions as well as dyke-like amphibolite bands in augen-gneiss. Farther northwest a prominent band of amphibolite separates the Gordonia Subprovince from the sheared Richtersveld rocks. Around Luderitz, pyroxenite plugs and numerous serpentinites in gneisses indicate the possible northwestern-most extension of this 700 km-long boundary line.

The Upington Terrane consists mainly of 2.0 Ga quartzite-pelite equivalents of the Kheis Subprovince sequence, overprinted by the main NW-trending Gordonia Subprovince folds and metamorphic zonation. Thrust-bounded structural domains of the Kheis Belt extend westwards into the Upington Terrane, where they are refolded, turned up on edge, and disrupted along the younger transcurrent shear zones so as to juxtapose lenticular crustal blocks of different stratigraphic, structural and metamorphic character (Stowe, 1983).

The northeastern boundary of the Upington Terrane is also the site of the Wilgenhoutsdrif Group, 1350 Ma greenstones, including pillow basalts, jaspilite and associated volcanoclastic sediments, thrust northeastwards across the older Kheis Belt quartzites. Thin serpentinites with talc schist and black chert occur in the thrust zones. These thrusts and recumbent folds are the oldest Namaquan structures recognized in this region of the Gordonia Subprovince, affecting only the northeast boundary. Closure of this volcanic (back-arc?) basin by imbrication with the 1.3 Ga Jannelsepan amphibolitic calcalkaline (arc?) complex, initiated the Namaquan orogeny, possibly by some form of arc-continent collision.

The Kakamas Terrane consists of 1.2–1.0 Ga juvenile crustal material and was subsequently the focus of late, transcurrent shears. Extensionally faulted basins developed along the northeastern outer margin of the Gordonia Subprovince, contain bimodal felsic-mafic volcanics and sedimentary rocks of the ~ 1150 Ma Koras Group east of Upington and of the Sinclair Sequence in southern Namibia.

The transition from the Jannelsepan amphibolitic complex to the Kakamas Terrane is abrupt across the main Brakbos-Dagbreek-Straussburg line of ~ 1.1 Ga shearing, and fold kinematic directions are totally different. Early isoclinal fold vergence changes from northeast in the Upington Terrane to southwest along the Bushmanland Subprovince boundary. Farther southeast, the Doornberg Line has been recognized as a major crustal discontinuity, conspicuous on the gravity surveys. This originated as a major thrust that was subsequently turned upon edge and was reactivated as a transcurrent shear (Coward and Potgieter, 1983; Stowe, 1984).

The Kakamas Terrane displays a northwest-trending fabric and was also the focus of the highest metamorphic grades, syn- to late-tectonic granites and charnockites. Around Kakamas (Fig. 3), the southwestern sector bordering the Bushmanland Subprovince consists of high-grade supracrustal rocks, distinctly different from either the Kheis or Bushmanland sequences. Paragneisses include "pink" leucogneisses, calc-silicates, quartzite and cordierite-sillimanite metapelite, interlayered with sheets of early-tectonic augen "grey" orthogneiss.

Early, syn- and late-tectonic plutons of the Gordonia Subprovince include 1.2–1.1 Ga biotite-hornblende gneissic granodiorites, non-foliated granitoids and charnockites. Geo-

chemical and mineralogical comparison of a granite from north-west of Upington with a Koras Group quartz porphyry, indicates that the Koras volcanics probably represent an extrusive phase of the late-tectonic plutons in the Gordonia Subprovince.

Most recent interpretations of Namaqualand geology tend to support some form of plate convergence, although the evidence may still be questioned. Sr isotopic evolution models suggest that the Jannelsepan "arc" assemblage, Wilgenhoutsdrif Group greenstones, and the late-tectonic granites represent a major juvenile crust-forming event, no older than 1.3 Ga (Botha and Grobler, 1979; Barton and Burger, 1983). In view of the observed thrusting, serpentinites, Jannelsepan Formation and Wilgenhoutsdrif Group volcanic assemblages, the Kakamas Terrane might conceal a geosuture formed when the southwestern part of the Gordonia Subprovince, together with the Bushmanland Subprovince, each with their distinctive structures and cover sequences, converged with the Kaapvaal continental block. Southwesterly vergent overthrusting has been reported from the western margin of the Gordonia Subprovince and nappe structures from the Aggeneys region of Bushmanland. The Bushmanland and Richtersveld Subprovinces may therefore be part of an exotic, older (2.0–1.6 Ga) microcontinent, accreted behind the Jannelsepan "arc" at about 1.3 Ga.

About 1800 km to the east in the Natal Belt, 1.2 Ga lavas, tuffs and metasediments occur in a tectonic melange beneath the amphibolitic Tugela nappe complex in northern Natal (Fig. 1). This has also been described as a major accretion of isotopically juvenile material, interpreted as representing an ophiolite obduction episode (Matthews, 1972). Intrusion of charnockite continued until ~950 Ma ago, significantly after the 1.2 Ga peak of high-grade metamorphism in the western Namaqua Province.

The younger, 1.1 Ga events in the western Namaqua Province and the Natal Belt might be explained by activation of a new, north-dipping, Cordilleran-type subduction zone, south of the previously accreted Natal-Bushmanland microcontinent, and along the Southern Cape Conductive Belt (De Beer and Meyer, 1983). Farther north, in the Gordonia Belt, transcurrent dextral shear and wrench fault zones developed along the old "suture," between the Gordonia and Kaapvaal Provinces, accompanied by uplift of extensive, high-grade regions in Namaqualand. During this event, diverse crustal lenses were tectonically juxtaposed along the main Brakbos and Doornberg shear systems (Fig. 5), late-tectonic granites were emplaced and the Koras Group "pull-apart" basins were formed. As summarized in the previous three paragraphs, the mosaic of diverse terranes in the Namaqua Province, may record multiple crustal suturing events.

Can the various "suspect terranes" and thrust-belts mapped along the northern and northeastern borders of Bushmanland and Gordonia be reconciled with the geophysical evidence suggesting oceanic subduction much farther south along the Southern Cape Conductive Belt? Does the Namaqua Province really conceal a cryptic record of multiple crustal amalgamation-accretion events? Did the first occur at 2.0 Ga, with convergence between the Richtersveld and Bushmanland Subprovinces? Was this followed at 1.3 Ga by collision between this amalgamated Proterozoic microcontinent and the older Kheis-Kaapvaal continent? Did oceanic crustal subduction and further are/microcontinent collision events continue along the Namaqua Province southern margin after 1.1 Ga?

These are some of the major questions posed by the Middle Proterozoic record of Southern Africa, to all of which a tentative "Yes" appears likely. Initial results of a new palaeomagnetic study of Namaqua rocks indicate that the various tectonostratigraphic terranes may be clearly distinguishable in patterns on NRM vector-component declination maps and

Figure 7: Pattern of tectonic terranes in the Damara Province. SCCB - "Southern Cape Conductive Belt." Horizontal hachures represent relict oceanic traces of the Adamastor geosuture: N - Nokaneng basic body; NNC - Naukluft Nappe Complex; M - Matchless Amphibolite; G - Grootderm metabasalts; B - Bridgetown metabasalts. M, G and B are linked by a prominent gravity anomaly on the inner continental shelf (dashed line). Late Proterozoic deep sedimentary basins, possibly floored by oceanic crust, are shown by 5 km to 10 km depth-to-magnetic-basement contours facing the marginal Ghanzi-Chobe Belt. Arrows denote tectonic vergence direction.

attempts are now being made to resolve different NRM acquisition ages by Ar-Ar thermochronometry (T.S. Onstott, personal communication, 1984).

The Late-Proterozoic Damara Province

The NE-SW trending branch of the Damara Orogen (Fig. 7) in central Namibia has been regarded as a typical example of intracratonic ensialic orogeny (Martin and Porada, 1977; Kröner, 1977) but geodynamic models involving various degrees of oceanic subduction have also been proposed (Hartnady, 1979; Barnes and Sawyer, 1980; Kasch, 1983). Summaries of Damaran geotectonic development have been provided recently by Coward (1983), Martin (1983) and Miller (1983a), covering also the cooperative work of groups from Britain (Leeds and Open University), Germany (Göttingen and Mainz) and South Africa (Council for Scientific and Industrial Research's National Geodynamics Programme involving several universities and state institutions).

Studies in the Damara Province were particularly concentrated in, and therefore biased towards, a high-grade upper amphibolite facies, partially anatexitically mobilized segment of the Damara Province in which exposed inliers of pre-Damaran crystalline basement rock are common. While easily accessible, superbly exposed, and well sectioned in the Namib Desert escarpment region, this area is atypical of the Damara Province as a whole.

In the southern, Gariep and Saldania Belts (Fig. 1), for example, regional metamorphic grades do not exceed the upper greenschist facies and older basement inliers are absent from their internal zones. They also contain a greater proportion of mafic-felsic low-grade metavolcanic material and a local abundance of immature semi-pelitic and meta-greywacke rocks. The terrane composition here is thus more "ensimatic" or island-arc related. Intensive isotopic studies of the crustal evolutionary type have not yet been undertaken in these areas, but it seems reasonable to predict that, if and when they are, the conclusions might differ considerably from those of central Damara Orogen studies.

The Damara Orogen (s.s.) of Namibia can be divided into several contrasted tectonostratigraphic zones or terranes, but the major divisions occur between the N-S trending, coastal Kaoko Belt (actually the African direct extension of the Brazilian Mantiquiera Province - Torquato and Cordani, 1981) and the NE-SW trending, "intra-cratonic," northern Swakop Belt and southern Khomas Belts. The junction (Coward, 1983) at which these three subprovinces meet is concealed beneath the central Namibian continental margin deposits and the temporal order of tectonic movements and terrane juxtaposition around it is therefore not absolutely certain. The convergence between the Kaoko-Swakop Belt and the Congo craton is considered to have occurred earlier, followed by Swakop-Khomas Belt convergence or transcurrent shearing around ~675-575 Ma (Coward, 1983), culminating finally at ~550-520 Ma in southeastward overthrusting of the Khomas Belt onto the southern Kalahari craton margin.

Damaran Sr and Nd isotopic studies show that many granitic rocks were derived from pre-existing continental crust and little new crustal material was generated during the main thermal event around 550 Ma (Hawkesworth and Marlow, 1983). Metasedimentary rocks low in the central Damaran sequence have isotopic characteristics very similar to the subjacent 2.0 Ga basement, but those of semi-pelitic schists high in the sequence appear to reflect the influx of large quantities of much younger (~1.0 Ga) material (Hawkesworth and Marlow, 1983). Its source could be an "underplated" 1.0-1.3 Ga lower crustal layer, but mixing between even mantle-derived 550-750 Ma volcanoclastic material and 2.0 Ga upper crustal erosional detritus is also a possibility.

Geodynamic reconstructions of the Damaran Orogeny generally assume some kind of subduction (Martin, 1983) but divide over the relative importance of continental ("ensialic") and oceanic models. The former invoke an early aulacogenic rifting stage (Martin and Porada, 1977) followed by a contractional stage driven by asymmetric "de-lamination" of subcontinental lithospheric mantle on the southern side of the trough (Kroner, 1982). The oceanic models assume that rifting was succeeded first by a sea-floor spreading stage and then by conventional subduction, but they differ over the question of whether the oceanic lithosphere involved was relatively wide (Barnes and Sawyer, 1980; Kasch, 1983) or narrow (Miller, 1983a).

The Khomas Belt is the main focus of intense asymmetric thrust-and shear-belt deformation where the highest metamorphic pressures, about 10 kbar, have been determined by microprobe analysis of co-existing minerals (Kasch, 1983). It is not, however, the zone of highest regional metamorphic temperatures, or igneous plutonic activity, which is roughly confined to the southwestern Swakop Belt, just north of the Okavango Lineament, associated with pressures in the 3-5

Figure 8: Geodynamic evolution of the Damara Province by closure of the Adamastor oceanic embayment. TRP is a tectonic rotation pole between Late Proterozoic Kalahari (K) and Congo (C) cratons, calculated from tectonic slip-vector data.

kbar range. Accordingly, the Khomas-Swakop pattern has been likened to a "paired," high P low T/low P high T metamorphic belt.

The southern Khomas zone is a deeply exhumed, southeasterly vergent fold-and-thrust belt, including a spectacular outlier klippe, the Naukluft nappe complex, and a variety of deeper thrust-system elements such as duplex structures, antiformal stacks and tectonic windows. Research is continuing on the stacking order, tectonic transport directions, later imbrication and partial refolding of thrust sheets in the southern marginal Khomas Belt or "Hakos-Auas Terrane." This correlates with new field evidence for the role of major overthrusting in the Gariep Belt to the south (Davies and Coward, 1982), and geophysical evidence of thrust belts along the buried northeasterly extensions in Botswana (Pretorius, 1984) and towards the Lufilian Arc and Zambezi Belt of Zambia.

The regional geometry of thrust zones and stretching lineations (Fig. 7) has recently been used to deduce tectonic transport in an evolving pattern of rigid-plate interaction at the complicated junction of the Lufilian-Zambezi (Damara age) and Mozambique orogenic belts in Central Africa (Coward and Daly, 1984). Contrary to previous models of "ensialic" orogeny in the Zambezi Belt, there is now speculation that oceanic crust was completely consumed along the Khomas-Zambezi convergent subduction zones, the resulting geosutures having been later rendered "cryptic" by development of large-scale transcurrent shear belts, e.g., the Mwembeshi Zone in southern Zambia. Coward (1983) and Coward and Daly (1984) considered the Okavango Lineament in central Namibia and the Mwembeshi Zone to be early sinistral shear belts.

The orientations of regionally consistent stretching lineations in central and southern Namibian thrust belts, and the large-scale pattern of vertical shear belts in the Pan-African belts of Zambia and Malawi, can be used for quantitative palaeo-plate-tectonic modelling (Hartnady, 1979). An Euler pole at 9°S, 28°E for convergent clockwise rotation of the Kalahari craton relative to the Congo craton (Fig. 8), assumes that the MZ and associated ENE-WSW (Luangwa-Kariba) shear belts are intracontinental transform structures with dextral shear sense. It also accounts for their apparent swing to more northerly trends in Malawi.

Late Proterozoic and older palaeomagnetic data from cratons on opposite sides of the Damara Province (McWilliams and Kroner, 1981) do not support wide ocean subduction models, although the Kalahari craton data in the critical 900-500 Ma time-interval is sparse and unreliable. A model of up to about 35° of angular closure about the above-mentioned Euler pole seems permissible and implies that a narrow (500-1000 km wide in the Khomas Belt region), northeastwards tapering ocean was created and later subducted between the Kalahari and Congo cratons between 900-600 Ma.

Figure 8 includes a Gondwanaland apparent polar wander (APW) swathe for the 1,000-700 Ma period, including sparse data from both cratons. Rotating the Kalahari craton 32° counter-clockwise about the tectonic rotation pole does not violate the APW swathe constraints, but actually groups the Gannakouriep Dyke swarm pole (GD on Figure 8) with East African palaeomagnetic data from similar ~800 Ma mafic volcanic and intrusive units. This approach resembles the Mesozoic-Cenozoic opening and partial closure of the Bay of Biscay during the Pyrenean phase of the Alpine orogeny. In such a scenario the Kalahari craton would be the Proterozoic analogue of the Iberian plate (Fig. 7).

The name Adamastor Ocean has been proposed by one of us (Hartnady) for this still hypothetical entity. Adamastor is a legendary demigod, turned to stone and personifying the Cape of Storms at the southern tip of Africa in an epic verse, the "Lusiad," by the 16th century Portuguese poet Camoes. Because of the Atlas and Iapetus association with names of "living" and "dead" North Atlantic oceans, this creative reworking of Greek mythology seems appropriate to apply in interpretations of the Damara Province in terms of the Wilson cycle. As a geotectonic concept, the Adamastor oceanic evolution not only provides a coherent explanation for a wide range of disparate phenomena in the southern Damara Orogen (Khomas Belt), Gariep, and Saldania Belts, but also has a bearing on interpretations of the Mesozoic development of the present rifted passive margin of the southwestern Atlantic.

Adamastor Ocean's relict existence in the southern Khomas Belt is indicated by the Matchless zone of MORB-like meta-volcanic and metaplutonic mafic rocks (Miller, 1983b) and numerous serpentinite bodies of depleted mantle-type geochemistry (Barnes, 1982) that are closely associated with major S to SE-vergent thrust-faults. Geochemical data from the meta-volcanic, "ophiolitic" Grootderm Formation in the Gariep Belt of southwestern Namibia indicate a "within-

plate" ocean-floor setting with strong hotspot or "plume-type" magmatic source affinities (Hartnady and Smith, in preparation). The Grootderm thrust sheet appears originally to have formed a high-standing volcanic edifice, created by an enriched magmatic source distant from any nearby terrigenous sedimentary provenances. It may therefore be an accreted upper part of an oceanic island-seamount chain (Kröner, 1975), an aseismic ridge or small oceanic plateau. The possibly significant role of hotspot materials in continental growth is now becoming more widely appreciated.

The Adamastor Ocean might have widened southwards beyond the Gariep and Saldania Belts into the broader realms of the Pampean Province of southern South America and the Transantarctic Province bordering the ancient cratonic region of East Antarctica. These extensions of the Pan-African or Brazilian orogenic systems (superprovinces) of West Gondwanaland appear to record a long history of "active margin" evolution between the Proterozoic supercontinent(s) and a Panthalassic Ocean, or perhaps a continuous evolutionary succession of different oceanic basins. The process of first accurately replacing this tectonic jigsaw puzzle into its end-Proterozoic configuration has barely commenced. Tracing it out fully over the previous 2.0 Ga of Earth history promises to be an absorbing but fascinating task.

Dr. Chris Hartnady is based at the Precambrian Research Unit (Dept. Geology, Univ. of Cape Town, Private Bag, Rondebosch 7700, South Africa), and has been involved in research and exploration in the Late Proterozoic Saldania, Damara, and Gariep Belts since 1966. He is also active in quantitative computer modelling studies, including research on the contemporary and Phanerozoic plate kinematics of Gondwanaland.

Prof. Pieter Joubert is Director of the Precambrian Research Unit. Previously a member of the Kenyan Mines and Geological Department and the South African Geological Survey, he has been involved in the exploration and study of Namaqualand since 1967.

Dr. Clive Stowe was a member of the Rhodesian Geological Survey and Reader at the University of Zimbabwe, prior to joining the Precambrian Research Unit. His research interests are structural geology and ore deposits, and he has worked on Proterozoic tectonics in the Northern Cape since 1979.

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